

Higgs searches at Tevatron

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Abstract.

SM and MSSM Higgs Searches at the proton anti-proton collider Tevatron in Run II are presented. The performance of the collider and the two experiments D0 and CDF is shown. No deviation from SM background expectation and no MSSM Higgs signal has been observed.

Keywords: Higgs, Tevatron

INTRODUCTION

The Higgs boson is the last missing particle in the Standard Model. Direct searches at LEP2 set a lower limit of $m_H > 114.4$ GeV at 95% confidence level (C.L.) on its mass. Further constraints by mass measurements of the top quark and the W boson and electro-weak parameter fits of the LEP Electro Weak Working Group suggest a rather light Standard Model Higgs boson. The electro-weak fit yields $m_H < 175$ GeV at 95% C.L., which extends to $m_H < 207$ GeV if the LEP2 limit is included.

Higgs production cross sections at the proton antiproton collider Tevatron are small. They reach $0.1 - 1$ pb depending on the Higgs mass. For Higgs masses below 135 GeV the Higgs is predominantly decaying into a $b\bar{b}$ quark pair. The dominant production mechanism $gg \rightarrow H$ suffers here an overwhelming multi-jet background. Searches can be performed with lower background in the associated Higgs production including a W or Z boson in the final state. The most promising channels are $WH \rightarrow \ell \nu b\bar{b}$ and $ZH \rightarrow \nu \bar{\nu} b\bar{b}$. For Higgs masses above 135 GeV the predominant decay channel is $H \rightarrow WW^{(*)}$ where at least one W boson is on-shell. Preferentially the leptonic decay channels $gg \rightarrow H \rightarrow WW^{(*)} \rightarrow \ell^+ \nu \ell^- \bar{\nu}$ and $WH \rightarrow WW^{(*)} \rightarrow \ell^\pm \ell^\pm + X$ can be explored.

EXPERIMENTAL ENVIRONMENT

Tevatron collider

In comparison to Run I, in which proton antiproton collisions have been taken place at the Tevatron collider at a center of mass energy of $\sqrt{s} = 1.8$ TeV, in Run II the center of mass energy has been elevated to $\sqrt{s} = 1.96$ TeV, giving rise to 10 % higher Higgs production cross sections. The bunch spacing has been reduced from 3500 ns to 396 ns. Major upgrades to the Linac and main injector together with a new antiproton recycler and electron cooling made it possible to achieve in Run IIa instantaneous luminosities of up to $170 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$.

Detector upgrades

The CDF and D0 detectors have been massively upgraded for Run IIa. Driven by physics goals they became very similar. Beside a replaced silicon tracker and central drift chamber the geometric acceptance of the CDF detector has been increased by new forward calorimeters and extended muon coverage. A new silicon tracker, new preshower detectors and a 2 T superconducting solenoid have been added to the D0 detector. Its muon coverage has been extended as well. The data acquisition and trigger systems have been upgraded for both detectors to cope with the shorter bunch spacing compared to Run I.

Of major importance for the Run IIb upgrade is the layer zero (L0) microvertex detector of D0 which is by the time of this writing inserted and fully read out. Its most remarkable feature is the signal to noise performance of $S/N = 18$.

Data samples

The Run II physics data taking started in 2002 (February for CDF and July for DØ). The reported Higgs search results are based on data taken until November 2005 and vary depending on the analysis channel between 261 and 950 pb⁻¹. This has to be compared to about 120 pb⁻¹ accumulated in Run I.

STANDARD MODEL HIGGS SEARCHES

$Z/\gamma^* \rightarrow ee + \text{jets (DØ)}$

The understanding and rejection of background is crucial in Higgs searches. Therefore the associated production of jets along with a pair of charge conjugated electrons originating from a Z/γ^* is investigated. The event selection encompasses two electrons above a transverse momentum of 25 GeV of which one has to be central ($|\eta| < 1.1$), any number of jets with a transverse energy above 15 GeV and an invariant di-electron mass of $70 < m_{e^+e^-} < 120$ GeV. The jet-multiplicity distribution of data is compared to simulation. While the event generator PYTHIA 6.319 shows more events in higher jet-multiplicity bins starting from three jets on, the matrix elements from the program Sherpa, which are matched to a parton shower via the CKKM mechanism, show good agreement for jet-multiplicity bins $N_{\text{jet}} \leq 4$.

$ZH \rightarrow \nu\bar{\nu}b\bar{b}$ (CDF)

In the ZH production considered here a Higgs is radiated from an off-shell Z boson which then becomes on-shell and decays into a neutrino antineutrino pair while the Higgs decays into a $b\bar{b}$ pair of heavy quarks. The crucial elements of the event selection consist of two jets with a transverse momentum above 60 and 25 GeV, of which at least one has to be b -tagged. To account for the two neutrinos which leave the collision undetected a missing transverse energy above 70 GeV is required. Backgrounds are W/Z production associated with heavy flavour jets, multi-jet production, di-boson production, mistagged b -jets and $t\bar{t}$ pair production. For a hypothesized Higgs mass of 120 GeV the events inside an invariant jet-jet-mass window between 80 and 120 GeV are counted. 289 pb⁻¹ of integrated luminosity are used. Six events are observed and 4.36 ± 1.02 events are predicted. This leads to a 95% C.L. exclusion limit of 4.5 pb.

$ZH \rightarrow \nu\bar{\nu}b\bar{b}$ (DØ)

The ZH analysis of DØ has an improved event selection with respect to the former analysis. It requires two acoplanar jets with a transverse energy above 20 GeV, missing transverse energy above 50 GeV and the scalar sum of the jets transverse energy to be below 240 GeV. The analysis is done for single and double b -tagged events separately to subdivide channels of highly different sensitivities. After derivation of the limits both channels are combined taking correlated uncertainties into account. For a hypothesized Higgs mass of 115 GeV the events inside an invariant jet-jet-mass window between 75 and 125 GeV are counted. An integrated luminosity of 261 pb⁻¹ has been used. 11 events are observed and 9.4 ± 1.8 are predicted, leading to an exclusion limit of 4.3 pb at 95% C.L.

Using this analysis, limits on WH production with a missed charged lepton can be placed. This improves the combined limits on WH production.

$WH \rightarrow \ell\nu b\bar{b}$ (CDF)

The WH analysis considered here expects either an electron or a muon and a neutrino from an on-shell W boson and a $b\bar{b}$ quark pair from the Higgs. To select events of interest the jets have to have a transverse momentum above 15 GeV, an electron or a muon above 20 GeV transverse momentum and missing transverse energy above 20 GeV. The analysis is done separately for single and double b -tagged events. The sensitivity of single b -tagged events has been increased by exploiting a Neural Network (NN) b -tagger which uses the information of different b -tagging variables, which are typically not 100% correlated. The double b -tagged events are chosen with a secondary vertex tagger since no improvement in sensitivity could be obtained in using the NN b -tagger. The analysis is based on an integrated

luminosity of 695 pb^{-1} . 332 events with at least one b -tagged jet are observed. The background consists of mistagged events, $Wb\bar{b}$, $Wc\bar{c}$, Wc , $t\bar{t}$, single top, di-boson and multi-jet production. The prediction of total background amounts to 318.8 ± 54.7 events. Limits are derived by fitting the di-jet invariant mass spectrum. For a hypothesized Higgs mass of 115 GeV an upper exclusion limit of 3.6 pb at 95% C.L. has been established.

$$WH \rightarrow \ell \nu b \bar{b} \text{ (DØ)}$$

Here, the WH analyses are done separately in the electron and the muon channel (plus the missed lepton channel as mentioned above in the ZH analysis). Further the single and double b -tagged events are treated separately and then combined later to drive a unique limit based on all decay channels and b -tag sub-samples. While the muon channel has been analysed for the first time at DØ the electron channel has been re-optimized. The event selection is based on one central isolated electron or muon with a transverse energy above 20 GeV. The missing transverse energy has to exceed 25 GeV and exactly two jets above a transverse energy of 20 GeV and within a pseudorapidity of $|\eta| < 2.5$ have to be found. At least one of them has to be b -tagged. The limit is derived from counting the number of events inside an invariant jet-jet-mass window around a hypothesized Higgs mass of 115 GeV. The integrated luminosity used varies slightly for the different WH search channels and ranges from 371 to 385 pb^{-1} . 32 single b -tagged events and six double b -tagged events are observed. The number of predicted events amounts to 45.1 ± 6.9 and 9.3 ± 1.8 . A combined exclusion limit of 2.5 pb at 95% C.L. can be established.

$$t\bar{t}H \rightarrow \ell + 2q + 4b \text{ (CDF)}$$

The Higgs production associated with a top antitop quark pair is investigated in the $t\bar{t}$ lepton plus jets channel where the top quarks decay into a b quark and a W boson, of which one decays leptonically and the other one hadronically, giving rise to a light $q\bar{q}$ pair. The Higgs is decaying into a $b\bar{b}$ quark pair. So there are altogether six jets expected in an event, among which four are supposed to be b -tagged. To distinguish the signal from background - which consists dominantly of mistagged events, irreducible processes with the same final state and multi-jet background - exactly one identified electron or muon is required. At least five jets with a transverse momentum above 15 GeV, among which at least three jets have to be b -tagged, are required. Missing transverse energy has to exceed 25 GeV to account for the neutrino. An integrated luminosity of 320 pb^{-1} has been used for this analysis. One event is being observed while 0.89 ± 0.12 background events are predicted. The exclusion limit on the associated production process for a hypothesized Higgs mass of 115 GeV is 0.95 pb at 95% C.L.

$$WH \rightarrow WWW^* \rightarrow \ell^\pm \ell^\pm + X \text{ (DØ)}$$

The WH production with three W bosons (of which at least two are on-shell) is considered in the final state with two like sign leptons, i.e. one lepton from the Higgs and one lepton from the associated W boson. In this way the background of Z bosons decaying into a pair of charge conjugated same flavour leptons can be removed very efficiently. The two like sign leptons are required to be isolated and having a transverse momentum above 15 GeV. In addition, missing transverse energy above 20 GeV is demanded to account for neutrinos. An integrated luminosity of 636 pb^{-1} has been used. In the ee -channel one event is observed while 0.70 ± 0.08 are predicted. In the $e\mu$ -channel three events are observed versus 4.32 ± 0.23 events predicted and finally in the $\mu\mu$ -channel two events are observed while 3.72 ± 0.75 are predicted. For a hypothesized Higgs mass of 115 GeV an exclusion limit of 3.88 pb could be set.

$$H \rightarrow WW^* \rightarrow \ell^+ \ell^- \nu \bar{\nu}, \ell = e, \mu \text{ (CDF)}$$

The Higgs invariant mass cannot be reconstructed in the case of leptonic W boson decay since the neutrinos leave the collision undetected. On the other hand one can exploit the spin correlation between the two leptons to discriminate background where two lepton candidates are not originating via a W boson from a scalar particle like the SM Higgs boson. The spins of the two W bosons originating from a scalar Higgs boson have to add up to zero. Due to the left-handed character of the electro-weak interaction ($W^{+(-)}$ bosons are only left (right) circular or longitudinal polarized)

the two leptons tend to be emitted collinear. To select the events two charge conjugated leptons are required. One of them has to have a transverse momentum above 20 GeV and the other above 10 GeV. Missing transverse energy has to exceed one forth of the hypothesized Higgs mass for which a limit is being derived. The invariant dilepton mass has to exceed 16 GeV and to be smaller than $m_H - 5$ GeV. An integrated luminosity of 360 pb^{-1} has been used. The difference in azimuthal angle between the two leptons is histogrammed and fitted to derive a limit. For a hypothesized Higgs mass of 120 GeV the exclusion limit at 95% C.L. is 4.5 pb.

$$H \rightarrow WW^* \rightarrow \ell^+ \ell^- \nu \bar{\nu}, \ell = e, \mu \text{ (DØ)}$$

The DØ analysis requires in the same final state two charge conjugated isolated leptons with a transverse momentum above 20 and 15 GeV. A veto on the Z resonance and energetic jets is applied. An integrated luminosity of 950 pb^{-1} has been used. For a hypothesized Higgs mass of 120 GeV 31 events are observed and 32.7 ± 2.3 are predicted, leading to an exclusion limit of 6.3 pb at 95% C.L.

STANDARD MODEL HIGGS LIMITS

Exclusion limits normalized to the SM cross section of all discussed analyses versus Higgs mass are shown in fig. 1. In the case of DØ a combination of all search channels is given, too. A combination of all Tevatron results, including those of CDF, is in progress.

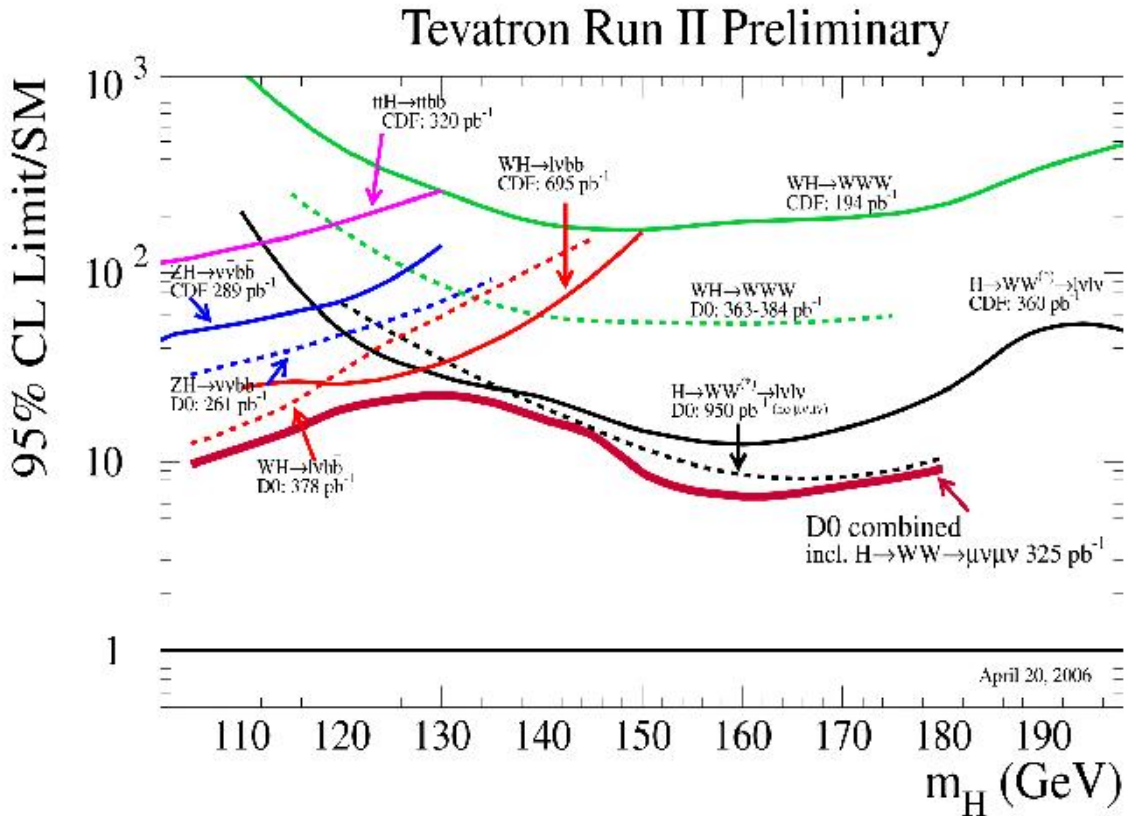


FIGURE 1. DØ and CDF Higgs exclusion limits normalized to the cross section predicted by the SM

MINIMAL SUPERSYMMETRIC SM HIGGS

Supersymmetric Particles and parameters

Five scalar particles are predicted in the MSSM: h, H, A, H^+, H^- . In CP-conserving models h and H are CP-even while A is CP-odd. At tree-level perturbation theory there are two independent parameters: the ratio of the vacuum expectation values $\tan\beta$ and the mass m_A . Five more parameters intervene via radiative corrections as shown in table 1. In supersymmetry one could have a light Higgs but with small couplings. 2×2 benchmark scenarios are studied [1], which are maximal and no-mixing scenarios for a positive and negative Higgs mass parameter μ .

TABLE 1. Susy parameters through radiative corrections and benchmark scenarios.

Parameter	Description	m_h -max	no-mixing
M_{SUSY}	Parameterizes squark, gaugino masses	1 TeV	2 TeV
X_t	Related to trilinear coupling A_t (\rightarrow stop mixing)	2 TeV	0
M_2	Gaugino mass term	200 GeV	200 GeV
μ	Higgs mass parameter	± 200 GeV	± 200 GeV
m_{gluino}	enters via loops	800 GeV	1600 GeV

Neutral MSSM Higgs $\rightarrow \tau\tau$ (DØ and CDF)

The signature of signal events is given by two reconstructed tau leptons and missing transverse energy. In the case of DØ different hadronic tau decay topologies are distinguished from each other and from quark and gluon induced jets by means of a neural network. Standard model backgrounds are $Z \rightarrow \tau\tau$ which is irreducible, $Z/\gamma^* \rightarrow ee, \mu\mu$, multi-jet production, $W \rightarrow \ell\nu$ and di-boson production. DØ used an integrated luminosity of 325 pb^{-1} and CDF used 310 pb^{-1} .

TABLE 2. Observed and expected event yields in Higgs to $\tau\tau$ search.

Experiment	Channel	Data	Expected background
DØ	$e + \tau_{\text{had}}$	484	427.3 ± 55.3 (stat \oplus sys \oplus lum)
	$\mu + \tau_{\text{had}}$	575	576.3 ± 61.5 (stat \oplus sys \oplus lum)
	$e + \mu$	42	43.5 ± 5.3 (stat \oplus sys \oplus lum)
CDF	$\tau_{1,2} \rightarrow X$	487	496 ± 54 (stat) ± 27.7 (sys) ± 24.8 (lum)

To derive limits the visible mass $M_{\text{vis}} = \sqrt{P_{\text{vis}}(\tau_1) + P_{\text{vis}}(\tau_2) + \cancel{E}_T}$ is being fitted. The numbers of observed and expected background events are given in table 2. Fig. 2 shows the exclusion plots in the plane of $\tan\beta$ and m_A for maximal mixing and no-mixing scenarios. LEP 2 limits are indicated as well.

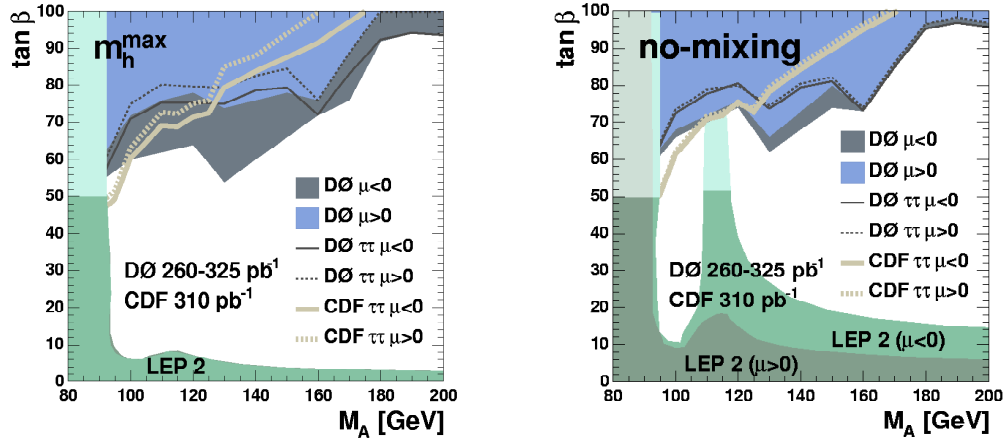


FIGURE 2. DØ and CDF Higgs into $\tau\tau$ exclusion limits in the $\tan\beta$ versus m_A plane for maximal mixing (left) and no-mixing (right) scenarios. Limits are indicated for both signs of the Higgs mass parameter μ . The results contain all τ decay channels.

Charged MSSM Higgs (CDF)

The SM top quark decays predominantly into a W boson and a b quark. The W boson of the top quark decay could be replaced by a charged Higgs boson if its mass is smaller than the top quark mass (subtracted by the b quark mass). The $t\bar{t}$ production is exploited in search for a charged Higgs, whose major decay modes are $H \rightarrow \tau\nu$, cs , $t^*b(\rightarrow)Wbb$ and $Wh(\rightarrow Wb\bar{b})$. The branching ratios depend on $\tan\beta$ and m_{H^\pm} and they are different from W boson branching ratios. An integrated luminosity of 193 pb^{-1} has been used. Final states with leptons and jets are selected as indicated by the different decay channels in table 3, where also the numbers of observed and expected events are given. The result is consistent with the SM. In fig. 3 the exclusion limits for a charged Higgs originating from a top quark, assumed to decay exclusively into $\tau\nu$ or cs are shown in the m_{H^\pm} versus $\tan\beta$ plane. The left plot shows the no-mixing scenario while the right plot shows the maximal mixing scenario. Exclusion limits from LEP experiments are also indicated.

TABLE 3. Observed and expected event yields in charged Higgs into $\tau\nu$, cs search. Non $t \rightarrow Wb$ expected background is indicated in a separate column.

Channel	Data	Expected background	SM expectation ($t \rightarrow Wb$)
$2\ell + \text{jets}$	13	2.7 ± 0.7	11
$\ell + \text{jets} (1b)$	49	20.3 ± 2.5	54
$\ell + \text{jets} (\geq 2b)$	8	0.94 ± 0.1	10
$\ell + \tau + \text{jets}$	2	1.3 ± 0.2	2

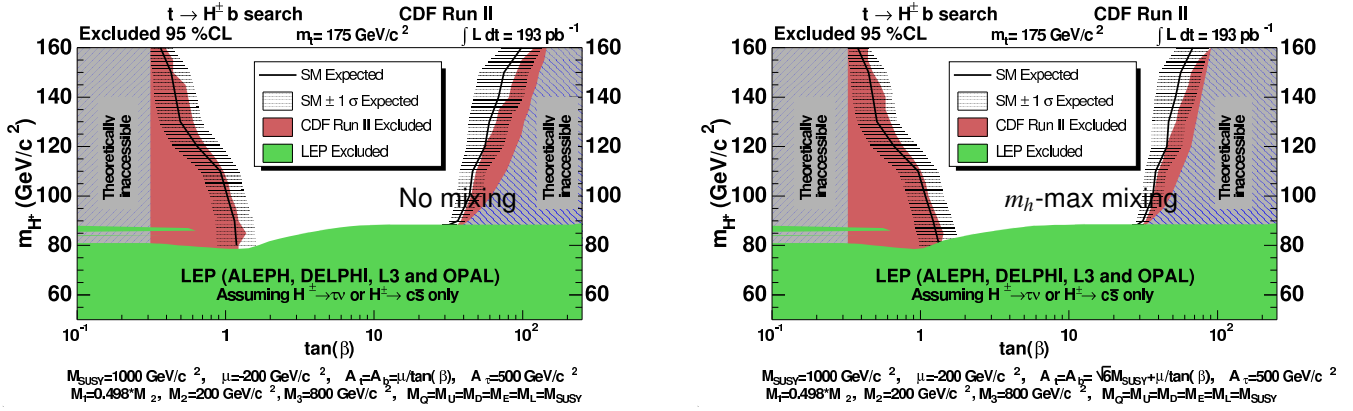


FIGURE 3. CDF exclusion limits for a charged Higgs originating from a top quark, assumed to decay exclusively into $\tau\nu$ or cs . The m_{H^\pm} versus $\tan\beta$ plane is shown for no-mixing (left) and maximal mixing (right) scenarios.

CONCLUSIONS

Tevatron and experiments are performing well. A wide range of Higgs searches has been performed by both, CDF and DØ experiments up to an integrated luminosity of 1 fb^{-1} in Run II. No deviation from the SM background expectation has been observed and no signal has been observed in MSSM Higgs search. Work to improve sensitivity is under way. A first combination of all SM Higgs channels has been presented by DØ. Combination efforts between DØ and CDF have started.

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REFERENCES

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